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ABSTRACT

Matter accreted on the surfaces of neutron stars consists of energetic particles of a few tens to a couple hundred MeV/nucleon, depending on the neutron star mass. In addition to heat, such particles produce nuclear reactions with the surface material. We propose that the recently observed 473 ± 30 keV spectral feature from the galactic center is gravitationally redshifted positron annihilation radiation produced at the surfaces of old neutron stars. The principal observational tests of the model would be the detection of nuclear gamma ray lines from the galactic center and redshifted positron annihilation radiation from the galactic disk.

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Johnson, Harnden and Haymes (1972) have reported low energy gamma ray observations from the galactic center region. These observations provide evidence for a statistically significant spectral feature at 473 ± 30 keV, with a total photon flux in the feature of $\sim 1.8 \times 10^{-3}$ cm^{-2} sec^{-1}. In the present paper we suggest that this observed line emission could be due to redshifted positron annihilation radiation produced at the surfaces of neutron stars. As a mechanism for positron production we propose nuclear collisions of accreted interstellar particles with the neutron star surface material.

Neutron star surfaces are generally believed to consist of Fe^{56} (Cameron 1970). However, if the accretion rate is sufficiently large, the surface composition should be significantly modified. The energy of an accreted particle at the surface of the neutron star ranges from about a few tens of MeV to a couple hundred MeV, depending on the neutron star mass (Table 1). Since a 100 MeV proton will traverse $X_p \simeq 10$g cm^{-2} of surface material before coming to rest, the amount of neutron star matter that is exposed to the accreted particles is of the order $4\pi R^2 X_p \simeq 10^{14}$g, where $R \simeq 10^6$ cm is the radius of a neutron star. If the accretion rate from the interstellar medium is $\sim 10^{11}$ g sec^{-1} (Ostriker, Rees and Silk 1970), the exposed material will be turned over by accretion every $\sim 10^3$ seconds. Thus, the surface composition will depend more on the composition of the incoming matter, diffusion processes into the interior, and possible nucleosynthesis on the surface, than on the original surface composition. The theoretical determination of the detailed surface composition of neutron stars affected by accretion appears to be a difficult problem which we shall not treat in the present paper. We propose instead that future gamma ray measurements may in fact determine this composition by observing characteristic line emissions. Some of these lines will be discussed below. Before doing so, however, let us first consider the 0.511 MeV line which should be only weakly dependent on the details of the composition, since positron emitters are almost always produced in the interaction of energetic protons with nuclei heavier than carbon.

We have calculated positron production by protons slowing down and coming to rest in material consisting solely of carbon, nitrogen and oxygen in ratios by number given by C:N:O = 0.5:0.1:1. (These ratios are the same as the relative ratios of C, N and O in Cameron's (1967) cosmic abundances). The principal positron producing reactions in CNO and their cross sections were summarized by Lingenfelter and Ramaty (1967) and Ramaty, Stecker and Misra (1970). Using these cross sections we may compute the positron yield per proton of energy E_p stopping in a material of the above composition. This yield is given by

$$Q(E_p) \simeq n_{CNO} \int_0^{X_p(E_p)} \sigma(E)\, dX , \tag{1}$$

where $\sigma(E)$ and $X_p(E)$ are the cross section and proton stopping range as functions of energy, and $n_{CNO} \simeq 4 \times 10^{22}$ is the number of target nuclei per gram of material. For protons of $E < 200$ MeV slowing down in CNO, $X_p(E) \simeq 2.5 \times 10^{-3}\ [E(\mathrm{MeV})]^{1.8}$ g cm^{-2} (Barkas and Berger 1964).

The positron yield per proton as evaluated from equation (1), after summation over all possible reactions, is given in Table 1 as a function of the incident energy E_p at the surface of the neutron star. This energy in turn depends on the neutron star mass which is also given in Table 1 along with the surface redshift Z_S(e.g. Borner and Cohen 1973).

As discussed above, the observational data indicate a line feature at 473 ± 30 keV. If interpreted as redshifted positron annihilation radiation, this feature requires redshifts ranging from about 0.016 to 0.13. In the calculation below we take an average redshift of 0.1, which, according to Table 1, corresponds to $M/M_\odot \simeq 0.6$, $E_p \simeq 65$ MeV and $Q^+ \simeq 0.02$. It is perhaps interesting to note that this interpretation of the observations has the consequence that the majority of old neutron stars have masses of less than about 0.8 $M_\odot$.

Because the stopping range of 0.5 MeV photons in CNO is about 30 g cm^{-2} (Storm and Israel 1967), and since on the average the positrons are produced at depths of the order X_p(65 MeV) $\simeq$ 5 g cm^{-2}, almost all upward moving photons are going to escape from the neutron star. Therefore, if the gamma ray production is isotropic, the photon yield at E_p = 65 MeV is also equal to 0.02 photons/proton.

For an accretion rate of 10^{11} g sec^{-1} or 6 x 10^{34} particles sec^{-1}, the redshifted positron annihilation radiation yield of a neutron star is 1.2 x 10^{33} photons sec^{-1}. Since the opening angle (FWHM) of the gamma ray telescope used by

Johnson, Harnden and Haymes (1972) is 24° in both latitude and longitude, the observed flux of 1.8×10^{-3} photons cm^{-2} sec^{-1} requires a neutron star density per cubic parsec in the galactic of $0.4Z^{-1}$ $[3.1 - \ln Z]^{-1}$, where Z is the thickness of the disk in kpc, and we have assumed a total length from the sun to the edge of the disk through its center of 20 kpc. Thus, for disk thicknesses of 0.2, 0.5 and 1 kpc, the required neutron star density is 0.42, 0.21 and 0.13 pc^{-3}, respectively. As we shall see below, these values are larger by factors of about 4 to 15 than the neutron star density near the sun obtained from soft x-ray observations. Therefore, in order to account for the observed ~473 keV gamma rays, we require an increase in the neutron star density toward the galactic center.

If the observed line feature at 473 keV comes entirely from a region around the galactic center, a total of 1.5×10^{10} neutron stars are required in the field of view of the detector at an average distance of 10 kpc. For a volume of 1.5×10^{10} pc^3 (Δl = 24°, ΔZ = 1 kpc), the neutron star density is 1 pc^{-3} or 0.6 $M_\odot$ pc^{-3}. This density does not exceed the density of stars in the central regions of the galaxy (Schmidt 1956).

An immediate consequence of nuclear collisions on neutron star surfaces is the emission of various other gamma ray lines redshifted by the same amount as the positron line. A detailed gamma ray spectroscopy of neutron stars will depend on the surface composition. Here we merely enumerate the potentially important lines resulting from the first excited states of C^{12}, N^{14}, O^{16}, Ne^{20},

Mg^{24}, Si^{28} and Fe^{56}. These are at 4.43 MeV, 2.31 MeV, 6.14 MeV, 1.63 MeV, 1.37 MeV, 1.78 MeV, and 0.85 MeV, respectively. We have calculated the yields per proton for the 4.43 and 6.14 lines for a pure CNO surface composition as used above (C:N:O = 0.5:0.1:1). From equation (1) and the excitation cross sections of C^{12*} and O^{16*} as summarized by Lingenfelter and Ramaty (1967), we obtain the yields listed in the last two columns of Table 1. Using these yields we predict fluxes of approximately 5 x 10^{-4} photons cm^{-2} sec^{-1} and 3 x 10^{-4} photons cm^{-2} sec^{-1} at 4.43 MeV and 6.14 MeV, respectively. It should be noted, however, that these predictions depend on the assumed composition of the neutron star surface.

The spectral feature at 473 keV has been interpreted by Fishman and Clayton (1972) as nuclear gamma rays from the deexcitation of cosmic ray Li^{7*}. Apart from considerable difficulties associated with the extremely large cosmic ray flux in the galactic center required to account for the observed spectral feature by Li^{7*} deexcitation, this mechanism also seems to conflict with the absence in the data of 0.51 MeV line emission from positron annihilation. Even if only $\lesssim$ 10 MeV/nucleon cosmic rays are present in the galactic center region as suggested by Fishman and Clayton (1972), such positrons would still be formed by the reactions $N^{14}(p,n)O^{14}$ and $N^{14}(p,\alpha)C^{11}$ which have maximum cross sections roughly at 8 to 12 MeV and 6 to 15 MeV, respectively (Andouze, Epherre and Reeves 1967; Jacobs et al. 1972). These maximum cross sections are comparable to the Li^{7*} excitation cross section, which peaks in the 3-5

MeV/nucleon region. Since the abundance of N^{14} in the cosmic rays is greater by about a factor of 5 than that of Li^7 (measured at high energies and not at $\sim$ 5 MeV where Li^7 may in fact be absent), the intensity of the 0.511 MeV line should at least be equal to the Li^{7*} deexitation line. Since there is no indication for the 0.511 line in the data, the feature at 473 keV cannot be due to Li^{7*} deexitation. This conclusion can be modified only if the cosmic rays have a very steep energy spectrum at $\sim$ 5 MeV, so that the number of particles in the range 3 to 5 MeV/nucleon greatly exceeds that in the 6 to 10 MeV/nucleon range. This is extremely unlikely, especially for Li^7, since this nucleus is generally believed to be a product of spallation reactions the threshold of which is invariably greater than 5 MeV/nucleon.

A necessary consequence of accretion on neutron stars is x-ray production. Ostriker, Rees and Silk (1970) and Silk and Weinberg (1972) have in fact suggested that the low-energy ($\sim$ 250 eV) diffuse x-ray emission from the galactic disk could be due to accretion on neutron stars from the interstellar medium. In order to account for the observations, this mechanism requires a neutron star density in interstellar space of $\sim 3 \times 10^{-2}$ pc^{-3}. Since the soft x-ray observations give information on nearby ($\sim$ 100 pc) x-rays sources, this neutron star density represents the density of such objects in the vicinity of the sun. The gamma ray observations discussed above require a neutron star density in the galactic center region of ~ 1 pc^{-3}, a value which is greater by about a factor of 30 than the local neutron star density as determined from soft x-ray observations. Such an increase is not inconsistent with the overall radial variation of the stellar density in the galaxy (Schmidt 1956).

It should be noted that Strittmatter, Brecher and Burbidge (1972) and Gorenstein and Tucker (1972) have pointed out difficulties with the accretion model on neutron stars as an explanation for the galactic soft x-ray background. If these difficulties are indeed real, we would consider the local density of 3×10^{-2} neutron stars per pc^3 as an upper limit only. An observational test of the neutron star accretion model for the soft x-ray background, however, would be the observation of redshifted positron annihilation radiation from the galactic disk. For an accretion rate of 10^{11} g sec^{-1} and a neutron star density of 0.03 pc^{-3}, the line intensity viewed by a detector of opening angle θ is given by 3.3×10^{-4} $Z[2.4 + \ln tg\, \theta/4 + \ln L/Z]$ photons cm^{-2} sec^{-1} rad^{-1}, where Z is thickness of the disk and L is the length of the disk in the direction of observation, both in kpc. For $\theta = 24°$, L = 10 kpc and Z equal to 0.2, 0.5 and 1.0 kpc, we get line intensities of 2.5×10^{-4}, 5.5×10^{-4} and 8×10^{-4} photons cm^{-2} sec^{-1} rad^{-1}, respectively. It should be pointed out, however, that Z = 1 kpc is quite unrealistic, since we do not expect that both the neutron star density and the interstellar gas density have scale heights of the order 0.5 kpc.

In addition to the redshifted positron annihilation radiation, 0.511 MeV photons will also be produced in the galactic disk from the annihilation of cosmic ray positrons. The problem of positron production in the interstellar medium has been considered in detail by Ramaty, Stecker and Misra (1970). A reasonable upper bound on the 0.51 MeV emissivity in the interstellar medium may be obtained by assuming that the ~ 1 MeV positron intensity as observed near earth, $j_+ \simeq 10^{-2}$ cm^{-2} sec^{-1} sr^{-1} (Cline and Hones 1970), is uniformly distributed throughout interstellar space and is dissipated solely by ionization losses and annihilation. This leads to a 0.51 MeV photon emissivity of $\sim 3 \times 10^{-25}$ cm^{-3} sec^{-1}. We can compare this emissivity with the emissivity in redshifted annihilation radiation from neutron stars in the solar neighborhood. For a neutron star density of 3×10^{-2} pc^{-3} and an accretion rate of 10^{11} g sec^{-1}, the latter emissivity is 1.3×10^{-24} photons cm^{-3} sec^{-1}, i.e., larger by about a factor of 4 than the nonredshifted emissivity. Because of various possible uncertainties, however, (mainly in the neutron star density and the cosmic ray positron intensity), this difference cannot be considered as significant, and we conclude that the redshifted and nonredshifted positron annihilation radiation emissivities in the galactic disk are approximately equal. Both these emissivities could lead to a line intensity of the order of 10^{-4} photons cm^{-2} sec^{-1} rad^{-1} from the galactic disk. The redshifted component of these line intensities, however, may be difficult to observe with a wide angle detector, because the universal background flux might be comparable to it if all galaxies produce the same amount of redshifted annihilation radiation as our own.

It has been recently suggested (Davidson and Ostriker 1972) that the pulsating x-ray sources Cen X-3 and Her X-1 could be binary systems where the x-ray energy comes from accretion on a neutron star. For example, the observed x-ray luminosity of Cen X-3, 10^{37} ergs sec^{-1} at a distance of 3 kpc, requires an accretion rate of 10^{17} g sec^{-1} and ~ 100 MeV/nucleon for each accreted particle on the surface of the neutron star. Provided that our assumptions on the surface composition are generally valid (i.e., the surface consists of CNO or heavier nuclei), an accretion rate of 10^{17} g sec^{-1} should produce about 10^{39} positrons sec^{-1} and a flux of redshifted annihilation radiation at earth of 10^{-6} photons cm^{-2} sec^{-1}. Even though this flux is below the presently available detector sensitivities, we would like to stress the importance of a future search for redshifted annihilation radiation from binary x-ray sources or from single nearby neutron stars.

Turning again to the galactic center observations, it would appear that $\sim 10^4$ sources such as Cen X-3 at 10 kpc could produce the 473 keV radiation observed by Johnson, Harnden and Haymes (1972). This, however, would imply x-ray sources in the galactic center radiating in the kilovolt range with a total luminosity of approximately 10^{41} erg sec^{-1}. Such an x-ray output is clearly in conflict with observational data (P. J. Serlemitsos, private communication), and thus rules out this mechanism for the production of the observed gamma ray line feature. For a given gamma ray flux, accretion from the interstellar medium produces the same total x-ray luminosity as accretion from binary companions, albeit the accreted energy is emitted in the ultraviolet and soft x-ray regions. Since photons of such energies are absorbed on scales of ≤ 100 pc, the power liberated by accretion on neutron stars from the interstellar medium in the galactic center region is not directly observable at earth.

Our mechanism of positron production by accretion on neutron stars as a possible source for the observed line feature at 473 keV from the galactic center is consistent with x-ray observations only as long as the rate of accretion per neutron star is sufficiently low (and hence the number of neutron stars is sufficiently large) so that the bulk of the accreted energy is radiated below ~ 1 keV. As we have discussed in this paper, accretion from the interstellar medium is a realistic possibility. Even though objects of the nature of Cen X-3 and Her X-1 seem to be inconsistent with the x-ray data, we cannot rule out the possibility that the observed redshifted annihilation radiation is produced by a larger number ($\gg 10^4$) of neutron stars in binary systems accreting matter at a slower rate ($\ll 10^{17}$ g sec^{-1}) than Cen X-3 and Her X-1.

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Table 1

Surface redshifts, incident proton energies and gamma ray yields as functions of neutron star mass. Per proton of given energy, Q^{+}, $Q^{(4.43)}$ and $Q^{(6.14)}$ are the yields for positron annihilation radiation, 4.43 MeV carbon line, and 6.14 MeV oxygen line, respectively.

Table 1

$M/M_\odot$	Z_S	E_p (MeV)	Q^+	$Q^{(4.43)}$	$Q^{(6.14)}$
0.37	0.053	39	0.0062	0.003	0.002
0.55	0.085	57	0.015	0.005	0.003
0.77	0.13	77	0.028	0.006	0.004
1.00	0.18	103	0.048	0.007	0.005
1.24	0.24	130	0.070	0.008	0.006
1.44	0.31	160	0.095	0.009	0.007
1.56	0.38	184	0.12	0.01	0.008
1.68	0.45	208	0.14	0.011	0.008
1.72	0.51	230	0.18	0.012	0.009